

Torrefaction of oil palm wastes

Yoshimitsu Uemura^{a,*}, Wissam N. Omar^a, Toshio Tsutsui^b, Suzana Bt Yusup^a

^aDepartment of Chemical Engineering, Universiti Teknologi Petronas, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia

^bDepartment of Chemical Engineering, Kagoshima University, 1-21-40 Korimoto, Kagoshima 890-0065, Japan

ARTICLE INFO

Article history:

Received 9 February 2010

Received in revised form 9 March 2011

Accepted 16 March 2011

Available online 27 March 2011

Keywords:

Torrefaction

Biomass

Empty fruit bunch

Mesocarp fiber

Kernel shell

ABSTRACT

This paper describes the effect of torrefaction on the basic characteristics of agricultural biomass wastes in Malaysia, such as empty fruit bunches (EFB), mesocarp fiber and kernel shell as a potential source of solid fuel. Mesocarp fiber and kernel shell exhibited excellent energy yield values higher than 95%. EFB, on the other hand, exhibited a rather poor yield of 56%.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Biomass is one of the promising renewable energy sources, and is utilized as solid, liquid and gas fuels. Especially, lignocellulosic biomass wastes are attracting interest worldwide, because of its non edible characteristic. In Malaysia, availability of oil palm wastes is the best among biomass wastes [1].

In order to utilize biomass wastes efficiently, the following drawbacks about biomass compared to fossil fuels must be solved properly:

- (1) Higher energy consumption for collection.
- (2) Heterogeneous and uneven composition.
- (3) Lower calorific value.
- (4) Difficult to transport.

Since it is very difficult to solve all the problems at the same time, we focus on the fourth problem in this paper. There are a few options to solve this; the major ones are pelletization, liquefaction and gasification. Though pelletization is the least expensive option, there are some problems associated with it; lower heat value and quality deterioration by moisture (pellet disintegration, moss growth and bioorganic decomposition). Recently, a low temperature treatment at 200–300 °C under an inert atmosphere has been found to be effective for improving the energy density and the shelf life of biomass. The treatment is called ‘torrefaction,’

and has been reported for wood and grass biomass rather recently. Arias et al. torrefied woody biomass (eucalyptus) at 240–280 °C, and found that the grindability of the biomass is improved [2]. Prins et al. proposed a kinetic model of torrefaction [3], and reported the details of torrefaction mass balance [4]. Some papers focused on the fuel quality [5] and the gasification feedstock quality [6,7] of the torrefied lignocellulosic biomass. Uslu et al. focused on comparison of torrefaction, fast pyrolysis and pelletization from the viewpoint of the international bioenergy logistics [8]. Currently, experimental torrefaction studies are mostly on woody and grass biomass; wood dusts [8], beech [3,4,6], eucalyptus [2], willow [3–5,7], larch [3,4], and canary grass [5]. Few academic papers have been found for torrefaction of agricultural lignocellulosic wastes, such as wheat straw [3–5], which are one of the promising renewable resources, especially in Southern Asia [1].

In 2008, Malaysia was the second largest producer of palm oil with 17.7 million tonnes, or 41% of the total world supply, while Indonesia was the world's largest producer of palm oil with 19.3 million tonnes of oil, or 45% of the total world supply. In 2008, productive oil palm plantations in Malaysia covered 4.5 million hectares, a 4.3% increase from the figures in 2007, which stood at 4.3 million hectares. The types of biomass residue generated by the oil palm industry include fronds, trunks, empty fruit bunches (EFB), mesocarp fiber and kernel shell. Fronds and trunks are generated at plantations. EFB, mesocarp fiber and kernel shell are generated at palm oil mills. Fig. 1 shows a process flow diagram of a palm oil mill [9]. EFB is the residue generated at the thresher, where fruits are removed from fresh fruit bunches. Mesocarp fiber is generated at the nut/fiber separator. Kernel shell is from the shell/kernel separator. The annual amount of lignocellulosic

* Corresponding author. Tel.: +60 5 368 7644; fax: +60 5 365 6176.

E-mail address: yoshimitsu_uemura@petronas.com.my (Y. Uemura).

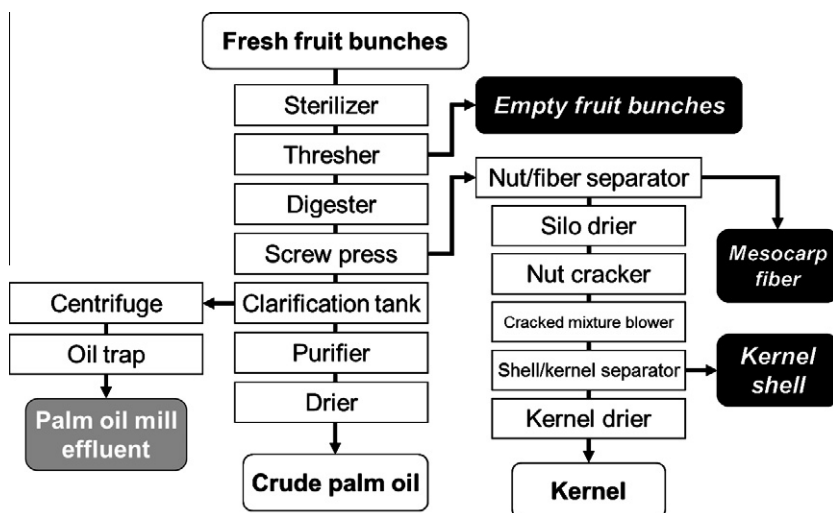


Fig. 1. Process flow diagram of palm oil mill.

residues generated by the oil palm industry is 140 million t, which corresponds to 17 Mtoe (million tons of oil equivalent). Since the current primary energy supply in Malaysia is about 70 Mtoe, the total oil palm biomass energy potential of 17 Mtoe may be able to contribute considerably to the decrease in consumption of fossil fuels (natural gas, coal and oil). Although torrefaction seems to be one of the key technologies to utilize these biomass residues efficiently in Malaysia, the problem is that no papers have been found for torrefaction of oil palm residues.

In this study, we focus on torrefaction of empty fruit bunches (EFB), mesocarp fiber and kernel shell of oil palm, which are typical agricultural wastes in Malaysia as shown in Fig. 1. The effect of torrefaction temperature on the mass and energy yields were investigated for those three types of biomass waste.

From this study, basic data for torrefaction of oil palm wastes were obtained. Another important finding is that the energy yield of mesocarp fiber and kernel shell showed 93% to 100%, whereas that of EFB showed rather lower values of 56% to 83%. From this finding, mesocarp fiber or kernel shell is preferable as a feedstock for torrefaction.

2. Experimental

2.1. Biomass samples

Three types of biomass waste utilized in this study, empty fruit bunches (EFB), mesocarp fibers and kernel shell, were collected at

an oil palm plantation in Kelantan, Malaysia in September 2009. They have been kept in a refrigerator maintained at below 5 °C, and used in this experimental work without any pretreatment.

2.2. Torrefaction experiments

Torrefaction of the biomass wastes was carried out using a horizontal tubular type reactor of 100 mm internal diameter, which is shown in Fig. 2. A prescribed amount of waste (around 6 g) was

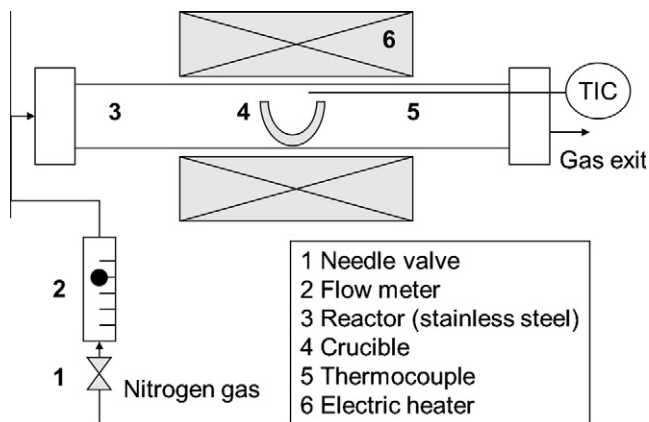


Fig. 2. A schematic diagram of the torrefaction reactor.

Table 1
Biomass samples used and their physical properties.

Biomass	Moisture	Calorific value [MJ/kg]				Elementary and ash analyses [wt%]						Form
		Wet (HHV)	Wet (LHV)	Dry (HHV)	Dry (LHV)	C	H	N	S	O	Ash	
EFB (measured in this study)	57.2	10.57	8.40	17.02	15.82	45.53	5.46	0.45	0.044	43.40	5.12	Fiber of 1 mm in diameter
EFB (literature)	65 [12]			19.1 [12]		48.8 [11]	6.30 [11]	0.20 [11]	0.20 [11]	36.7 [11]	7.3 [11], 4.6 [12]	
Mesocarp fiber (measured in this study)	37.2	13.33	11.48	19.61	18.31	46.92	5.89	1.12	0.089	42.66	3.32	Fiber of 1 mm in diameter
Mesocarp fiber (literature)	42 [12]			18.8 [12]		47.2 [11]	6.00 [11]	1.40 [11]	0.30 [11]	36.7 [11]	8.4 [11], 6.1 [11]	
Kernel shell (measured in this study)	21.4	16.14	14.55	19.78	18.49	46.68	5.86	1.01	0.06	42.01	4.38	Irregular bowl like chip of 10 mm long and 2 mm thick
Kernel shell (literature)	17 [12]			20.1 [12]		52.4 [11]	6.30 [11]	0.60 [11]	0.20 [11]	37.3 [11]	3.2 [11], 3.0 [12]	



Fig. 3. Photos of raw materials and torrefied samples.

weighed, and put in a crucible. The crucible was placed at the center of the reactor. After flushing the reactor with nitrogen, the temperature of the reactor was raised to different desired levels of 220, 250 or 300 °C at a constant rate of 10 °C/min by an electric furnace surrounding the reactor. After 30 min torrefaction, the heater was turned off and the reactor was left to cool down to the ambient temperature. Then the torrefied sample was recovered, weighed and kept in an air tight vessel. Throughout the procedure described above, 0.5 L/min of nitrogen was flowed through the reactor. The experiment was repeated 3 times.

2.3. Measurements

For the three biomass wastes (wet) used in this study, the moisture content and the calorific value were measured. For the dried biomass wastes and the torrefied samples, the calorific value, elementary (CHNS) composition and ash content were measured.

The moisture content was measured as follows. A prescribed amount of sample (3 g) was weighed in a crucible, and was placed in an electric oven maintained at 105 °C. After 24 h of drying, the sample was weighed every one hour till the decrease in weight became negligibly small.

The calorific value was measured using a bomb calorimeter, model C2000 series manufactured by IKA-WERKE. The calorific value from a bomb calorimeter is the high heat value (HHV), which includes the latent heat of the vapor emitted from the specimen. Values of HHV obtained by the measurement were converted to those of the low heat value (LHV) using Eq. (1) [10]. LHV is more realistic than HHV, because LHV does not contain any contribution from the latent heat of the vapor.

$$LHV = HHV - (21.987w_H + 2.443w_W) \quad (1)$$

Where LHV and HHV are in MJ/kg; w_H is the hydrogen mass fraction of the specimen; w_W the free water fraction. Elementary (CHNS) analysis was carried out using CHNS-932 supplied by LECO Corporation. The ash content was measured as follows. A prescribed amount of sample (1 g) was weighed in a crucible, and was placed in an electric furnace and the temperature was raised to 700 °C. After 3 h, the furnace was turned off and was allowed to cool down; the crucible containing the ash was weighed.

The biomass wastes used in this study are summarized in Table 1. According to Table 1, the moisture content, the calorific value and the elementary analysis result in this study show fairly close values with those from literatures [11,12]. The small differ-

Table 2a
Results of mass measurement.

Biomass	Treatment	Mass before treatment (g)	Mass after treatment (g)	Mass yield (%)	Average mass yield (%)
EFB	Dried	2.8082	1.2014	42.78	–
	Torrefied at 220 °C	3.4110	1.3487	39.54	43.16
		1.8911	0.8314	43.96	
		2.3900	1.0991	45.99	
	Torrefied at 250 °C	6.4128	2.2603	35.25	36.98
		4.4916	1.7266	38.44	
		6.6550	2.4787	37.25	
	Torrefied at 300 °C	6.3099	1.4542	23.05	24.18
		6.5354	1.4935	22.85	
		6.3296	1.6865	26.64	
Mesocarp fiber	Dried	6.4749	4.0638	62.76	–
	Torrefied at 220 °C	3.4517	2.1025	60.91	63.08
		3.6146	2.2058	61.02	
		1.6547	1.1136	67.30	
	Torrefied at 250 °C	5.2471	3.2563	62.06	60.04
		3.1097	1.8113	58.25	
		4.9903	2.9843	59.80	
	Torrefied at 300 °C	3.4237	1.8285	53.41	52.45
		3.9638	2.1992	55.48	
		3.8091	1.8459	48.46	
Kernel shell	Dried	3.5679	2.8056	78.63	–
	Torrefied at 220 °C	8.7237	6.4597	74.05	77.44
		6.9499	5.5361	79.66	
		9.3999	7.3899	78.62	
	Torrefied at 250 °C	10.2515	7.787	75.96	73.83
		10.8957	7.896	72.47	
		4.3388	3.1703	73.07	
	Torrefied at 300 °C	9.9687	7.2555	72.78	71.27
		7.7522	5.5179	71.18	
		8.6267	6.0267	69.86	

ence between this study and the literatures can be acceptable because those properties vary depending on surrounding conditions and harvesting season [13].

3. Results and discussion

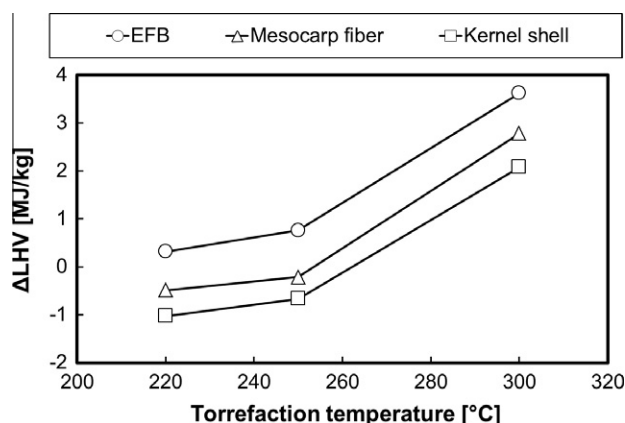
3.1. Appearance of torrefied samples

In this study, three types of oil palm waste were torrefied. In Fig. 3, photos of all the samples including raw materials and torrefied samples are exhibited. The color of EFB and mesocarp fiber becomes darker as the torrefaction temperature increases. Particu-

Table 2b

Results of calorimetry, elementary and ash analyses.

Biomass	Treatment	Calorific value (MJ/kg)			Elementary and ash analysis (wt.%)									
		HHV	LHV	Δ LHV	C	Δ C	H	Δ H	N	S	O	Δ O	Ash	Δ Ash
EFB	Dried	17.02	15.82	–	45.53	–	5.46	–	0.45	0.044	43.40	–	5.12	–
	Torrefied at 220 °C	17.17	16.14	0.32	46.75	1.22	4.68	–0.77	1.27	0.12	41.42	–1.98	5.75	0.63
	Torrefied at 250 °C	17.67	16.58	0.76	47.07	1.54	4.95	–0.51	1.35	0.11	42.24	–1.16	4.28	–0.84
	Torrefied at 300 °C	20.41	19.44	3.62	49.56	4.03	4.38	–1.08	1.27	0.02	43.19	–0.21	1.58	–3.54
	Dried	19.61	18.31	–	46.92	–	5.89	–	1.12	0.09	42.66	–	3.32	–
Mesocarp fiber	Torrefied at 220 °C	19.03	17.82	–0.49	46.93	0.01	5.50	–0.38	1.83	0.10	43.30	0.64	2.34	–0.98
	Torrefied at 250 °C	19.24	18.09	–0.22	47.70	0.77	5.20	–0.69	1.74	0.10	40.18	–2.48	5.10	1.78
	Torrefied at 300 °C	22.17	21.10	2.78	48.60	1.68	4.87	–1.02	2.14	0.09	40.03	–2.63	4.26	0.94
	Dried	19.78	18.49	–	46.68	–	5.86	–	1.01	0.06	42.01	–	4.38	–
Kernel shell	Torrefied at 220 °C	18.85	17.46	–1.03	45.87	–0.81	6.31	0.45	0.40	0.02	43.07	1.06	4.33	–0.05
	Torrefied at 250 °C	19.07	17.82	–0.67	51.89	5.20	5.71	–0.15	0.47	0.01	38.50	–3.51	3.42	–0.96
	Torrefied at 300 °C	21.68	20.56	2.07	54.21	7.52	5.08	–0.78	0.50	0.02	36.66	–5.35	3.53	–0.85

**Fig. 4.** Change in calorific value (torrefied against dried) as a function of torrefaction temperature.

larly, EFB torrefied at 300 °C exhibits almost black color. A similar tendency was observed for a woody biomass in a previous paper [6].

3.2. Calorific and CHNS analysis

The results of mass measurement, calorimetry, elementary and ash analyses for the dried and torrefied samples are listed in Tables 2a and 2b. In general, for all the three type of biomass waste (EFB, mesocarp fiber and kernel shell), torrefaction resulted in a higher calorific value and a higher carbon content. In order to discuss more specifically, the calorific value, the CHO contents and the ash content (the change against the dried sample) are plotted against the torrefied temperature in Figs. 4–6, respectively. From Fig. 4, it is found that the tendency of LHV against torrefaction temperature is similar quantitatively among the three types of biomass waste used in this study. The heating value LHV of the biomass is an important value as a solid fuel. The heating value of all the samples increases with temperature. This tendency is consistent with the previous works [2,5,7], and is mainly due to the carbon content increase (Fig. 5a) and the oxygen content decrease (Fig. 5c). The hydrogen content decreases as torrefaction temperature increases except for one exception (Fig. 5b). This decrease in hydrogen and oxygen is due to dehydration and de-carbon dioxide from the biomass during the torrefaction [4,7]. The dried EFB containing 45.53 wt.% of C, 5.46 wt.% of H and 43.40 wt.% of O (see Table 2b) is expressed as $\text{CH}_{1.5}\text{O}_{0.7}$. It is obvious that either CO_2 or H_2O emission will result in decrease in H and O contents of the EFB.

From Fig. 6, it is difficult to recognize a certain temperature dependency of the ash content on torrefaction temperature. From

the result of EFB in Fig. 6, the ash content showed a tendency to decrease with torrefaction temperature. This tendency for EFB was not observed for mesocarp fiber or kernel shell. At a temperature of 650 °C, higher than the torrefaction temperatures used in this study, Noda et al. [14] reported that 90% of sodium and 20% of potassium move from the solid phase to the gas phase during pyrolysis of several types of lignocellulosic biomass. This may be attributed to vaporization of alkali salts, specifically alkali halides, in the biomass. At the torrefaction temperatures used in this study, substantial vaporization is not likely to occur because the vapor pressure of alkali halides at 220–300 °C is thought to be quite lower than at 650 °C. The decreasing tendency observed for EFB in this study, therefore, may be attributed to the inhomogeneity of the biomass.

3.3. Yield of torrefaction

The mass and energy yields of the dried and torrefied samples were calculated, based on equations used by Bridgeman et al. [5]. The mass and energy yields (Y_{mass} and Y_{ene}) are defined by Eqs. (2) and (3), respectively.

$$Y_{\text{mass}} = 100 \times (\text{mass after drying or torrefaction} / \text{mass of wet sample before the treatment}) \quad (2)$$

$$Y_{\text{ene}} = Y_{\text{mass}} \times (\text{LHV after treatment} / \text{LHV before treatment}) \quad (3)$$

The energy yield used by Bridgeman et al. [5] is in HHV basis. The energy yield used in this study is in LHV basis.

Fig. 7a–c shows the mass and energy yields under different conditions for EFB, mesocarp fiber and kernel shell, respectively. Among the results, the mass of torrefied samples treated at 220 °C, the lowest temperature, showed almost the same decrease in mass as that of dried at 105 °C. This indicates that the extent of torrefaction for the samples treated at 220 °C was negligible compared with those at 240 °C and 300 °C from the viewpoint of change in mass. As the torrefaction temperature increases, the mass yield decrease steadily, whereas the decreasing ratio is depending on the waste type; EFB has the highest decreasing ratio and kernel shell has the lowest.

There are two main causes for the decrease in mass of the dried or torrefied samples. One is moisture loss, another thermal decomposition to form volatile or gaseous products such as H_2O , CO , CO_2 , acetic acid and other organics [7]. The decrease in mass for the dried and 220 °C-torrefied samples is thought to be mainly caused by the loss of moisture. In other words, substantial torrefaction did not occur for the biomass samples used in this study at 220 °C. For torrefaction at higher temperatures (240 and 300 °C), the decrease is attributed to the thermal decomposition of the hemicellulose part of the biomass [3].

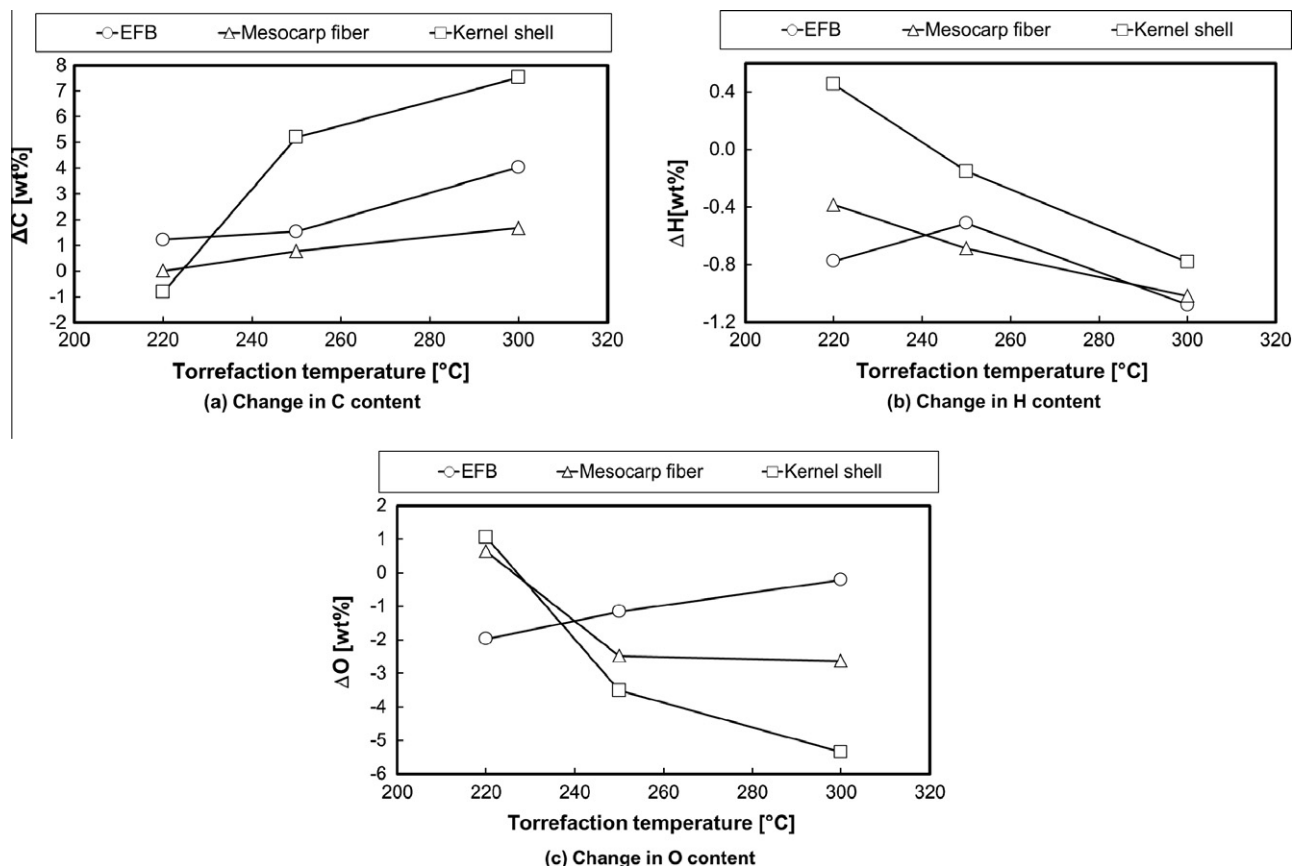


Fig. 5. Changes in (a) C, (b) H and (c) O contents (torrefied against dried) as a function of torrefaction temperature.

When the mass yield of EFB, mesocarp fiber and kernel shell is compared, it is obvious that EFB shows the lowest value among the three as pointed out previously, even based on the dried sample. This means that EFB decomposed more than the other two during the torrefaction. Abdullah and Gerhauser reported that the ash in EFB enhanced the decomposition of the EFB [15]. In our study, the EFB has the highest ash content among the three types of biomass used. This high ash content in our EFB might have caused the lowest mass yield.

The energy yield in Fig. 7 ranges from 56% to 100% depending on the feedstock and its treatment condition. The energy yield of the dried samples would be 100%, if only moisture loss occurs during the treatment. The results of mesocarp fiber and kernel shell

(Fig. 7b and c) are consistent with this rule, whereas the energy yield of the dried EFB (Fig. 7a) is 80%, quite less than 100%. This means that EFB decomposed to some extent even during the drying.

The energy yield of torrefied EFB decreases steadily from 83% to 56% with the temperature, whereas those of torrefied mesocarp fiber and kernel shell maintain almost 100% regardless of torrefaction temperature. This difference is mainly due to the poor mass yield of EFB because the calorific value of all the three types of biomass increased to the similar extent by torrefaction as shown in Table 2b or Fig. 4.

3.4. Comparison with other types of lignocellulosic biomass

Some torrefaction studies for woody and grass biomass have been reported recently [2–8]. In order to compare our results with the previous studies, the H/C atomic ratio was plotted against the O/C ratio for the raw biomass (circled) and the torrefied samples in Fig. 8. As torrefaction proceeds, both the ratios, H/C and O/C, decrease in parallel. In general, this tendency is common among our results and those reported in previous papers. This is mainly due to chemical removal of water and carbon dioxide [4,7] as discussed previously. From this figure, it is found that torrefaction of oil palm wastes (EFB, mesocarp fiber and kernel shell) proceeds similarly to those of other lignocellulosic biomass, such as wood and grass.

It is worthwhile to mention that major ash components are different between woody biomass and oil palm, and this may result in a different decomposition rate. The major three mineral components in woody biomass are Ca (average 972 ppm), K (average 796 ppm) and Mg (154 ppm) [16]. On the other hand, oil palm con-

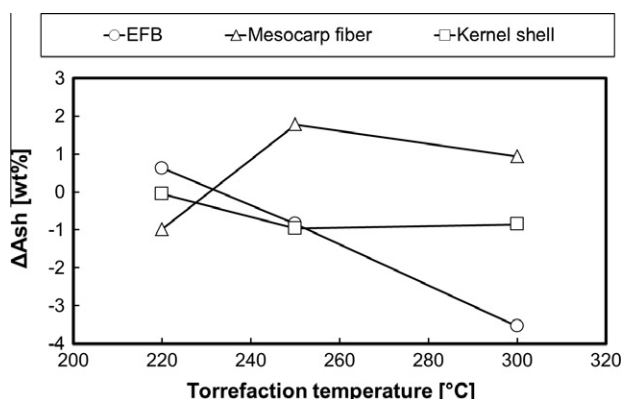


Fig. 6. Change in ash content (torrefied against dried) as a function of torrefaction temperature.

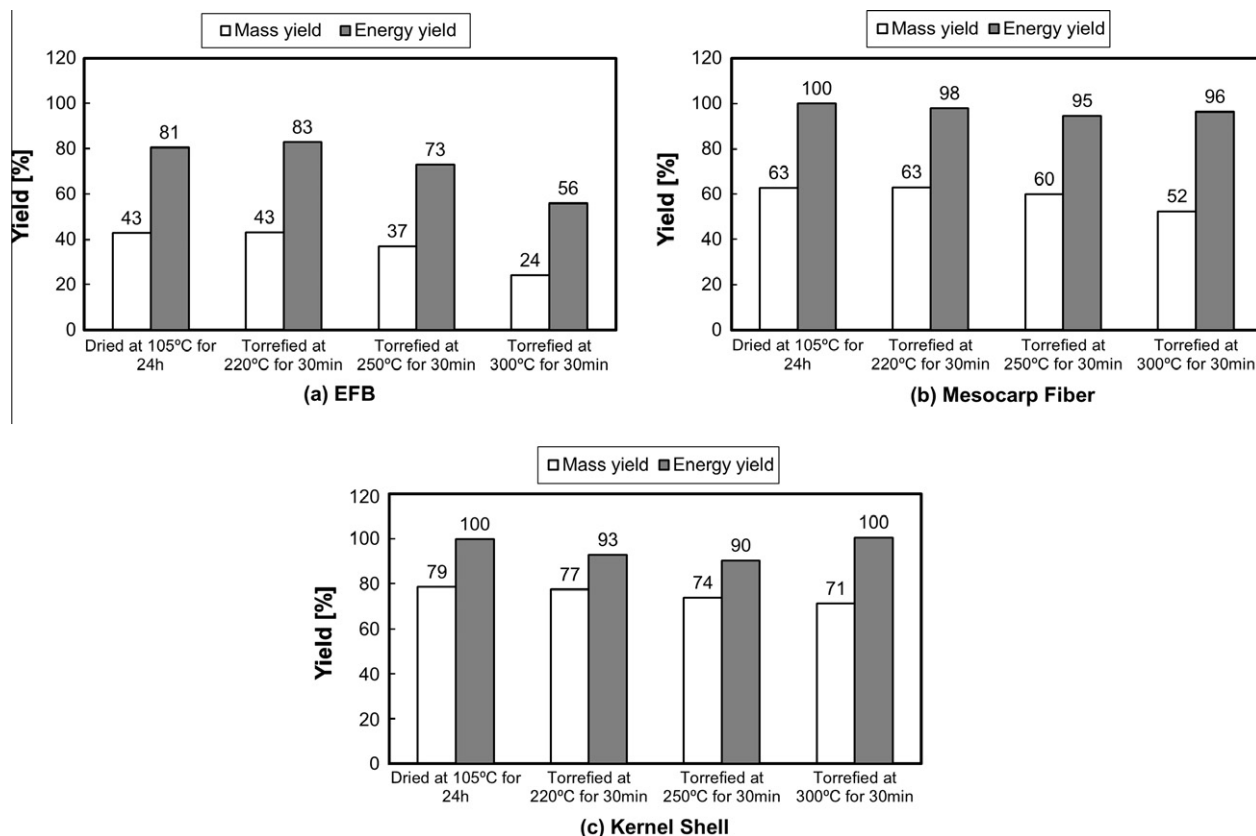


Fig. 7. Mass and energy yields for (a) EFB, (b) mesocarp fiber and (c) kernel shell.

tains K (whole palm 1.60 wt.%), Ca (whole palm 0.18 wt.%) and Mg (whole palm 0.16 wt.%) [9]. As we discussed in the section IIIC, the ash content especially the potassium content in the oil palm tree could enhance the biomass decomposition. Therefore, we should be careful about the high potassium content in the ash and its effect on the torrefaction kinetics.

4. Conclusions

In this study, torrefaction of empty fruit bunches (EFB), mesocarp fiber and kernel shell of oil palm, which are typical agricultural wastes in Malaysia, was experimentally conducted. The effect of torrefaction temperature on the mass and energy yields was investigated for those three types of biomass waste. Mesocarp fiber and kernel shell showed excellent energy yield values of 96% and 100%, respectively. EFB, on the other hand, exhibited a rather poor yield of 56%.

The biomass samples used in this study did not undergo any pretreatment, because of a practical reason that no treatment is the cheapest way in industry. According to a previous paper [17], for a cylindrical biomass pellet of less than 1 mm, the process of thermal decomposition at 643–873 K is controlled by the primary reactions, not by other transfer processes. That is why our results in this paper may be free from the mass and heat transfer effects. The authors are planning to conduct more experiments using the same biomass types to further understand the torrefaction mechanism.

Acknowledgment

The authors acknowledge that this work was supported financially by the Mitsubishi Foundation.

References

- [1] Suzana Y, Mohamad TA, Uemura Y, Anita R, Lukman I, Shuit SH, et al. Review on agricultural biomass utilization as energy source in Malaysia. In Proceedings of the 16th ASEAN regional symposium on chemical engineering, manila; Philippines, 1–2 December 2009. p. 86–9.

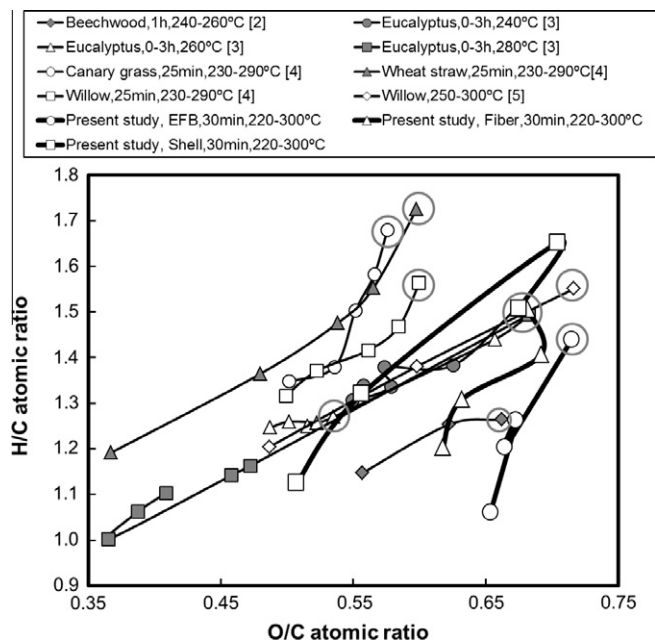


Fig. 8. Comparison of H/C vs. O/C tendency.

- [2] Arias B, Pevida C, Feroso J, Plaza MG, Rubiera F, Pis JJ. Influence of torrefaction on the grindability and reactivity of woody biomass. *Fuel Process Technol* 2008;89:169–75.
- [3] Prins MJ, Ptasiński KJ, Janssen FJJG. Torrefaction of wood Part 1. Weight loss kinetics. *J Anal Appl Pyrolysis* 2006;77:28–34.
- [4] Prins MJ, Ptasiński KJ, Janssen FJJG. Torrefaction of wood Part 2. Analysis of products. *J Anal Appl Pyrolysis* 2006;77:34–40.
- [5] Bridgeman TG, Jones JM, Shield I, Williams PT. Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. *Fuel* 2008;87:844–56.
- [6] Couhert C, Salvador S, Commandré J-M. Impact of torrefaction on syngas production from wood. *Fuel* 2009;88:2286–90.
- [7] Prins MJ, Ptasiński KJ, Janssen FJJG. More efficient biomass gasification via torrefaction. *Energy* 2006;31:3458–70.
- [8] Uslu A, Faaij APC, Bergman PCA. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletization. *Energy* 2008;33:1206–23.
- [9] Corley RHV, Tinker PB. *The oil palm*. 4th ed. Oxford: Blackwell Science; 2003. p. 328.
- [10] Asano K. *Chemical process calculation*. 2nd ed. Tokyo: Kyoritsu; 1999. p.127.
- [11] Mahlia TMI, Abdulmuin MZ, Alamsyah TMI, Mukhlishe D. An alternative energy source from palm wastes industry for Malaysia and Indonesia. *Energy Convers Manage* 2001;42:2109–18.
- [12] Wahid MB. Renewable resources from oil palm for the production of biofuels. In: *Proceedings for the international conference on biofuels*, Kuala Lumpur, Malaysia; 5–6 July, 2007. p. 163–9.
- [13] Núñez-Regueira L, Rodríguez-Añón JA, Proupín-Castiñeiras J, Vilanova-Diz A, Montero-Santoveña N. Determination of calorific values of forest waste biomass by static bomb calorimetry. *Thermochemica Acta* 2001;371:23–31.
- [14] Noda R, Matsuhisa Y, Ito T, Horio M. Alkali metal evolution characteristics of wood biomass during pyrolysis and gasification. In: *Proceedings for the Annual Meeting of the Japan Institute of Energy*, Japan, 30 July, 2003. p. 196–7.
- [15] Abdullah N, Gerhauser H. Bio-oil derived from empty fruit bunches. *Fuel* 2008;87:2606–13.
- [16] Johdai S, Sameshima K, editors. *Chemistry, Wood Science Series*, vol. 4. Ohtsu: Kaisei-sha; 1993. p. 77.
- [17] Jalan RK, Srivastava VK. Studies on pyrolysis of a single biomass cylindrical pellet – kinetic and heat transfer effects. *Energy Convers Manage* 1999;40:467–94.